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CONDUCTIVE POLYMER SENSOR ARRAYS—A NEW FRONTIER TECHNOLOGY FOR CBM

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Abstract: Today's commercial and military aircraft require significant manpower resources to provide operational readiness and safety of flight. Aging aircraft fleets are much in need of new and innovative health-monitoring methods to prevent catastrophic failure and reduce life-cycle costs. The key needs of characterizing in situ structural integrity characteristics of corrosion and barely visible impact damage (BVID) to determine the "damage susceptibility" must be addressed. This paper presents a new concept for performing onboard real-time monitoring using conductive polymer sensor array technology.

Using conductive polymer thick film (PTF) technology and elastomer materials, Honeywell is developing a family of low-cost sensor-on-film technology (SOFT) capable of sensing temperature, moisture, vibration, structural impact and, strain quantities. These sensors conform to surface profiles (6 to 10 mils thick) adding little weight and can be easily replicated to provide deeply distributed and highly redundant web architecture solutions. The SOFT approach is based on the novel idea of directly integrating sensory, control, and data processing electronics into the system of interest (vehicle, space-borne structure, etc.). The polymer sensory system is proposed to conform to the shape of the platform into which it would be integrated, or in other words, be "conformal," which by definition means to "have the same shape or contour". The technical approach defines the novel idea of using a polymer film as a flexible substrate, on the backside of which electrical interconnects, sensory functions, and data processing electronics would be directly integrated. The sensory functions are defined by incorporating polymer thick-film patterns on the film surface which can then be bonded to the platform of interest to perform failure prevention diagnostics.

Key Words: Conductive polymer sensor, sensor arrays, conformal sensor, condition-based maintenance

Background: Both commercial and military service personnel currently employ "walk-around" structural inspection as a cornerstone for performing condition-based maintenance. This means that a hierarchy of inspections is required to ensure that fleet readiness and availability requirements are met. Structural inspection includes daily inspection, phased maintenance based on aircraft operating time, conditional inspection based on the mission and location of the aircraft, and calendar-based inspection.

Although condition-based maintenance inspection is mature and performed reliably in most cases, its application in future military and commercial systems has significant drawbacks:

- High Cost—Currently, the cost to maintain a Navy aircraft is up to $200,000 per year. A 1996 Naval Center for Cost Analysis AMOSC report indicates that the direct cost of maintaining Navy aircraft and ships is at least $15.0 B per year. As much as 25% to 30% of operating revenue is spent on maintenance activities for commercial air carriers.

- Manpower-Intensive Effort—According to a 1995 study performed by the office of the Under Secretary of Defense, 47% of the Navy's active duty enlisted force (173,000 sailors) and 24% of the Marine Corps (37,600 marines) are assigned to maintenance functions. The mandate to reduce manpower while performing duties faster, cheaper, better, and with increased reliability is a reality in both military and commercial transportation segments.

In addition to these issues, problem areas exist specifically for maintaining structural integrity, including:

- BVID—The increased use of composite materials in aircraft structures introduces the potential for BVID, a maintenance-induced damage effect. At least 30% of all maintenance performed is related to structural repair due to tool dropping, in-service damage, etc.

- Hidden and Inaccessible Corrosion—A significant amount of structural integrity loss is due to hidden corrosion as well as corrosion located in inaccessible areas (wheel wells, landing gear areas, fuel tank, etc.). The practice of applying surface treatments of various types to provide adequate protection, in some cases overcoating the surface with several layers, causes considerable weight increase. This increase results in loss of fuel savings and aircraft performance.

Technical Approach:

Trade Study Results: This section summarizes a trade study performed to identify and assess potential aircraft inspection areas that could benefit from conductive polymer sensor array technology. The trade study involved the identification of seven key areas of a generic fighter aircraft (F-18 or equivalent). The areas addressed in the study were external wing structure, internal wing and fuselage structure, including landing gear and cockpit canopy, communications, external stores, and empennage structure. Figure 1 is a drawing of the F-18 aircraft showing the functional layout of the seven aircraft sensing areas for possible future technology insertion. The sensing areas are mapped to the aircraft geometry, labeled by area, and keyed with the full-scale trade study chart shown in Table 1. For each sensing approach, three packaging options exist: (1) a conformal sensor array, which would cover a larger surface area such as an external wing area over several square feet; (2) a conformal sensor applique to provide sensing coverage in a smaller area (a few square inches, possibly with significant contour shapes); and (3) a conformal boot assembly. The conformal boot design would involve the fabrication of a

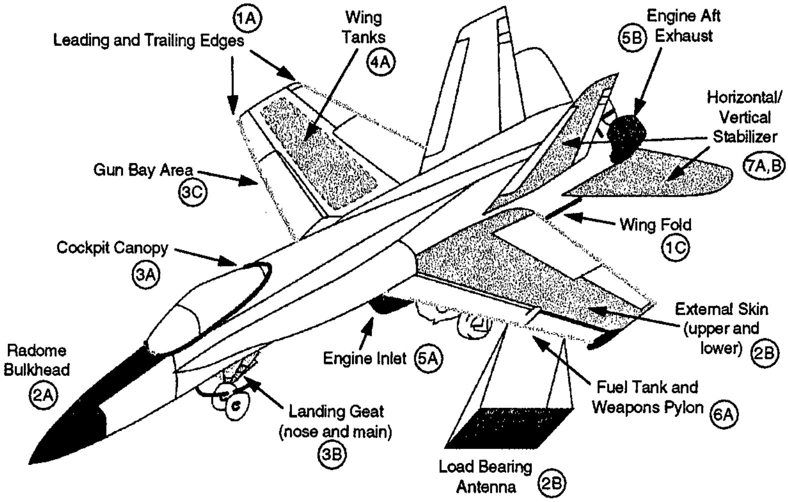

Figure 1. Key Sensing Locations on Aircraft

Table 1. Aircraft Trade Study Chart

Aircraft Area		Part/Assembly	Problem Definition	Sensing Approach*	Sensing Configuration
1	Wing External	• Leading edges • Trailing edges	• Flap and drive assembly • Impact (BVID) • Corrosion—wing attach fitting • Erosion	• M/C • ID	• Conformal array • Conformal boot
		• External skin (upper and lower)	• Impact (BVID due to maintenance/ repair) • Corrosion (fastener area)	• M/C • ID	• Conformal array • Conformal applique
		• Wing fold	• Corrosion in hinge area • Wing attachment fatigue	• M/C	• Conformal tape
2	Communications Support	• Radome bulkhead • Wing antenna	• Corrosion (dissimilar ± F-galvanic) • Phased-array antenna	• M/C • LBA	• Conformal boot • Conformal applique
3	Fuselage	• Cockpit canopy	• Corrosion—dissimilar interface (galvanic)	• M/C	• Conformal applique
		• Landing gear	• Corrosion in wheel well area, main landing gear assembly	• M/C	• Conformal applique
		• Gun bay area	• Corrosion—dissimilar interface	• M/C	• Conformal applique
4	Wing Internal	• Wing tank	• Fuel leakage in web area (wet bay) • Electrical connector/ground straps	• M/C	• Conformal applique
5	Engine	• Engine inlet • Aft engine exhaust area	• Impact (BVID) to debris/bird strike • Corrosion—moisture	• ID • M/C	• Conformal applique
6	External Stores	• Fuel tank pylon • Weapons pylon	• Corrosion—dissimilar interface • Erosion	• M/C	• Conformal applique
7	Empennage	• Horizontal stabilizer • Vertical stabilizer box	• Pivot shaft corrosion • Corrosion	• M/C	• Conformal applique

* M/C = Moisture/Corrosion; ID = Impact Detection; LBA = Load-Bearing Antenna

preformed structure—a sensory boot that fits the spatial constraints of the aircraft contour shape. An example of this configuration would be a preformed boot fit over the leading edge or radome bulkhead assembly.

Sensor Development: This section describes details of the conductive polymer sensor array design [1] that provides the capability for performing multifunction conformal sensing. Also presented are the sensory applications for using the linear sensor array to detect corrosivity characteristics as an outer aircraft skin or below floorboards, impact forces that can cause BVID and electromagnetic energy.

Polymer Sensor Array Design: Honeywell has developed polymer sensors to sense moisture (i.e., electrolyte) conditions and the presence of moisture/fluids over an extended surface area. A primary maintenance concern is the need to sense and quantify moisture trapped between the protectant system layer and aircraft surface that could cause corrosion to occur. Typically, the moisture is an electrolyte, an electrically conducting fluid that has ions in solution. The polymer sensor array has been designed to detect the "presence" of an electrolyte, which can be seawater, acid rain, lavatory fluids, fuel, hydraulic fluid, chemicals, or cargo by-products.

The basic design is implemented by printing on a flexible substrate material with a specific pattern design, curing it, and layering it with a pressure-sensitive adhesive. A typical pattern developed for electrolyte sensing is a transducer design with alternating electrode pairs. Figure 2 illustrates the pattern layout for a polymer sensor array. The figure shows a set of dedicated electrode pairs, each of which operates as a sensory element. The sensor is designed to function as a linear 2-D array that measures the "location" where the electrolyte is sensed and the "amount" of electrolyte based on exposure across the sensor array.

Detection of Corrosivity: Four conditions must exist before corrosion can occur: (1) presence of a metal that will corrode an anode; (2) presence of a dissimilar conductive material (i.e., cathode) that has less tendency to corrode; (3) presence of a conductive liquid (electrolyte); and (4) an electrical path between anode and cathode. A corrosion cell is formed if these four conditions exist due to the electrochemical effect, as shown in Figure 3. In future aircraft, paintless appliques will be applied to the surface of the metal to act as a moisture barrier to protect the bare metal from being exposed to the electrolyte. The applique film layer (6.0-mil-thick fluoropolymer film) prevents the corrosion cell from functioning by separating the electrolyte from the anodic and cathodic sites on the metal surface. If this layer is damaged due to erosion, heat exposure, or aging, the cell is activated, which causes corrosion to occur.

Figure 3 also highlights the concept of using a polymer sensor array to detect corrosive susceptibility. A polymer sensor array is patterned on the backside of applique film layer using standard ink-jet printing techniques. The applique is then bonded to the aircraft surface via a pressure sensitive adhesive (PSA) layer. The sensor array then operates to sense the "conductivity" of the trapped fluid by conducting a current through the fluid located between IDT electrode pairs. The fluid's conductivity property is, by definition, "the ability to act like an electrolyte and conduct a current, or a measure of its corrosivity."

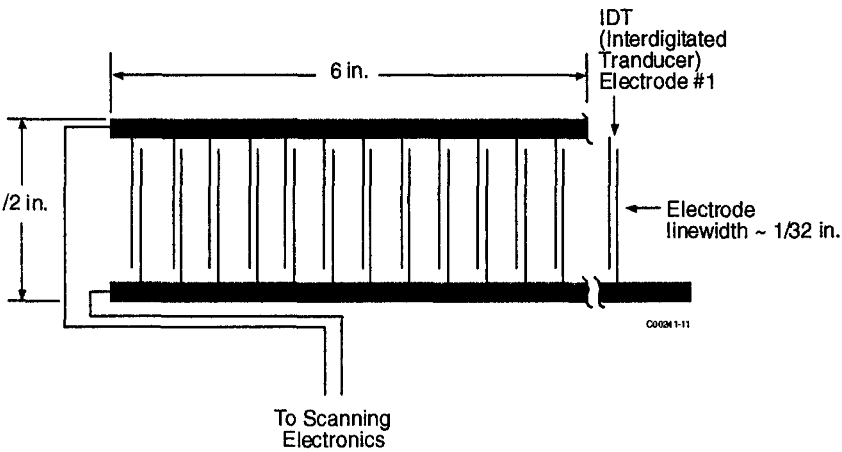

Figure 2. Pattern Layout of Polymer Sensor Array

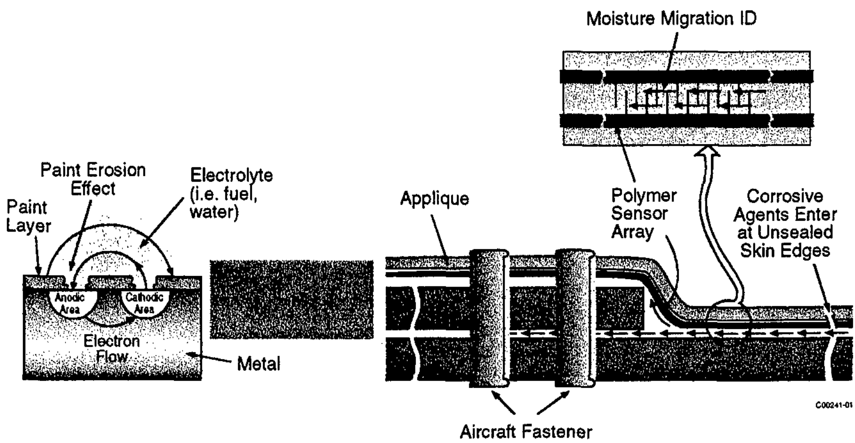

Figure 3. Smart Corrosion Sensing Concept

The concept of performing corrosive environmental "exposure susceptibility" index monitoring to minimize scheduled inspections and provide direct cost savings is shown in Figure 4. The basic idea is to continuously monitor the actual exposure of each aircraft to corrosive environmental factors (moisture ingress into protective coating, type of corrosive agent, etc.) and then schedule corrosion inspections based on these measurements, rather than on preset rules that are only loosely related to corrosion. Typical preset rules that an exposure susceptibility index would replace are calendar-based (i.e., inspection every 30 days) or usage-based (i.e., inspection every 10 hr of operation) inspections. One can think of the system as a "corrosion odometer" with a

readout that steadily increases according to the corrosiveness of the environment to which the aircraft is exposed. Maintenance personnel can intermittently check the odometer and perform inspections as needed.

$$I = \int dt \cdot F(W, Cl, C, T)$$

W ≡ Humidity, Wetness
Cl ≡ Concentration Level of Index
C ≡ Corrosivity
T ≡ Temperature

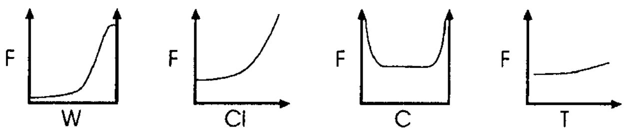

Figure 4. Exposure Susceptibility Index

The sensor array approach is capable of sensing and calculating an exposure index to ingress of an electrolyte (i.e., water) and the "wetness" effect of the electrolyte. The wet/dry cycle of exposure is a strong indicator of how susceptible an aircraft is to corrosion, with wetness being a basic requirement for corrosion to occur. The wetness exposure index is defined as the integral over time of the function $F_W(W)$. Here W is the time-varying output of a "wetness" sensor (1 = wet, 0 = dry) and quantifies the total corrosive effect of wetness. F_W is a simple function that gives the exposure index in a convenient scale, so an abbreviated inspection is called for each time the index passes through a multiple of 100, for example. Thus, for severe environments such as in Puerto Rico, an increase by 100 every 15 days could occur, as compared to an increase by 100 every 90 days in Denver.

Further improvement to the exposure susceptibility index can be obtained by adding other environmental factors that can influence corrosion. These include the concentration level of the electrolyte, temperature, and conductivity (corrosivity factor).

Figure 5 illustrates the index calculation concept, showing the maintenance cost savings concept in detail. The design approach is set up to collect and analyze the environmental factors related to structural health (moisture ingress, impact forces, etc.) that could lead to loss of structural integrity. These factors are collected and integrated as a "cumulative index" to determine (1) the level of "susceptibility" to failure and (2) whether maintenance is required at a given location in the aircraft. The cumulative index value is envisioned to be represented as simple whole number from 0 to 100 (which indicates the level of susceptibility, with a higher number indicating more potential for damage may exist) that could be read out by maintenance personnel from the aircraft maintenance debriefing interface at scheduled inspection intervals. The crew could then make a decision to perform scheduled maintenance or bypass the action, which reduces overall operating cost by reducing inspection time.

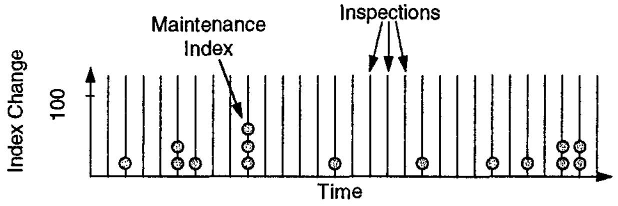

Figure 5. Maintenance Cost Savings Tutorial

Impact Detection: The polymer sensor implemented for moisture/corrosion sensing is also capable of sensing impact forces caused by maintenance-induced damage or operational servicing. To provide sensing for impact forces, the polymer sensor array is configured with an additional semiconductor polymer layer, as shown in Figure 6. The design approach is set up to operate as a force-sensing resistor (FSR). An FSR operates on the principle of converting force applied via a structural impact event to an equivalent voltage output. As pressure is applied, individual electrode pairs are shunted, causing a decrease in electrical resistance. The measurement of impact force magnitude, impact direction vector along the sensor array, and impact surface area can be quantified depending on polymer composition, shunt pattern and shunt shape, and the method for applying pressure (hemispherical vs. flat). Figure 7 shows the typical curve of sensor response. The figure is a plot of electrical resistivity vs. applied force with an active sensing region of two to three orders of magnitude from low impedance (kilohms) to high impedance (megohms). Over a wide range of applied pressure, the sensor response is approximately a linear function of force. The first abrupt transition that occurs is at low pressure. This point is called the "breakover point" where the slope value changes. Above this region, the force is approximately proportional to 1/R until a saturation region is reached. When force reaches this magnitude, applying additional force does not decrease the resistance substantially.

Figure 8 is a photo illustration of a commercially available off-the-shelf FSR product called Uniforce, which has an operating range of 0-1000 psi.

Another type of conductive polymer sensor is a polymer matrix sensor, which consists of electrically conducting and nonconducting particles suspended in a matrix binder material. Figure 9 shows a cross-sectional view of a polymer matrix sensor. Typical design construction includes a matrix binder and filler. The choice of matrix binder materials can include polyimides, polyesters, polyethylene, silicone, and other nonconducting materials. Some typical filler materials include carbon black, copper, silver, gold, and silica. Particle sizes typically are on the order of fractions of microns in diameter and are formulated to reduce temperature dependence, improve mechanical properties, and increase surface durability. Applying an external force to the surface of a sensing film causes particles to touch each other, decreasing the overall electrical resistance.

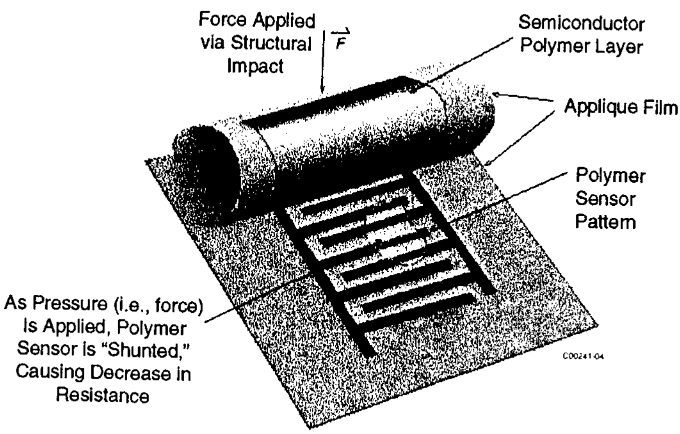

Figure 6. Force-Sensing Resistor (FSR)

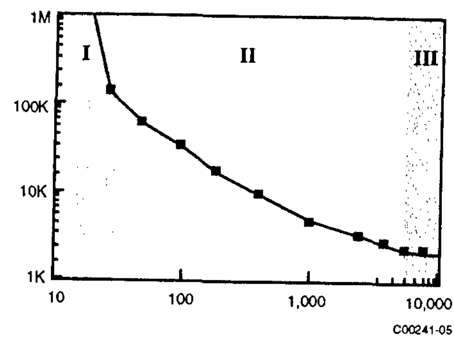

Figure 7. FSR Response vs. Applied Force

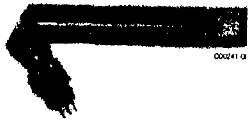

Figure 8. Example of Off-the-shelf FSR Product

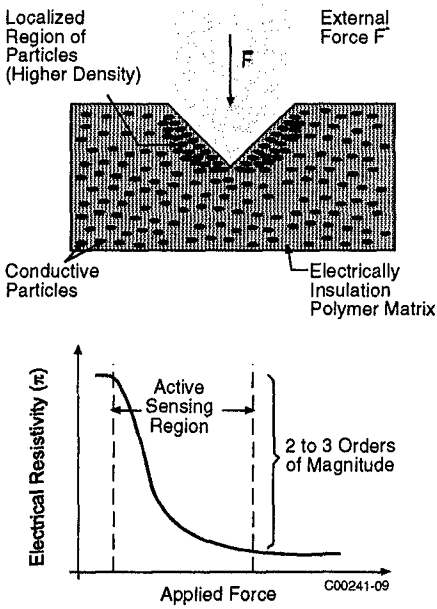

Figure 9. Polymer Matrix Sensor

Table 2 illustrates the typical performance properties for polymer thick-film (PTF) resistor technology and other resistor technologies. The table includes a summary for thin films, semiconductor, and continuous metal films. The significant advantage of PTF resistor technology over all other resistor sensing is the cost to fabricate devices. The PTF cost factor is achieved by the ability to print resistive material via stencil, screen printing, and ink-jet printing techniques.

Table 2. PTF Resistor vs. Other Resistor Technology

Resistor Type	Gauge Factor (G)	TCR (ppm/°C)	Application Method	Relative Cost
Continuous metallic films	2.0	20.0	• Spin cost	High
Thin film	50.0	20.0	• RF sputter • Evaporation	High
Semiconductor	50.0	1500.0	• Diffused • Implanted	Medium
Thick Film (PTF)	10.0	50.0–500.0	• Screen print • Stencil • Spin cost	Low

Source: G. Harsanyi (Ed.), *Polymer Films in Sensor Applications—Technology, Materials, Devices and Their Characteristics,* Technomic Publication, 1995.

A prime example of how FSR technology could be used for aerospace sensing is structural integrity monitoring. Today's commercial and aerospace structures incorporate a large amount of composite materials to reduce structural weight and increase load-bearing properties. Composites are susceptible to damage due to impact forces experienced in operation, including debris picked up from runways and maintenance-induced damage caused by tool dropping. Figure 10 illustrates the system-level concept of impact-damage-detection-based applied force vs. damage for a composite aircraft panel. A matrix array of FSR elements is shown integrated into the aircraft panel. Panel construction involves printing FSR elements directly on the panel surface or on a film layer, which is then bonded to the panel via a pressure-sensitive adhesive layer. The polymer patterns incorporated on the panel include a combination of sensor elements and electrical interconnects implemented with conductive polymer materials.

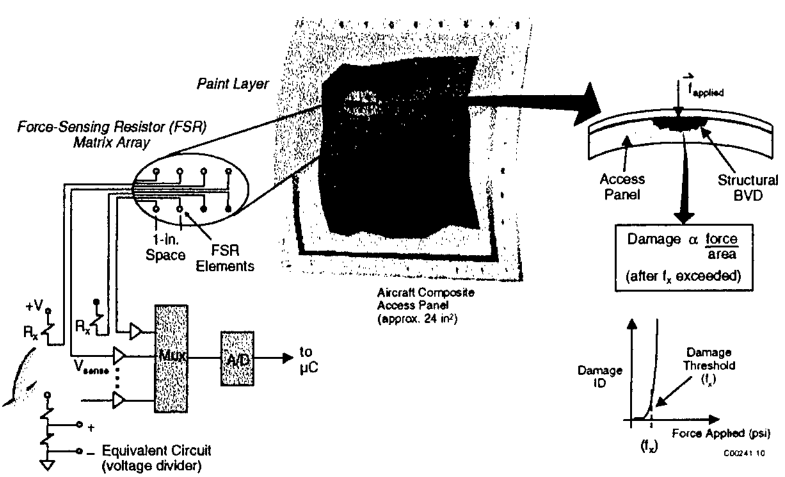

Figure 10. Structural Impact Damage Tutorial

To measure and record impact forces in real time, the output of each FSR element is converted to an equivalent voltage via a simple voltage divider circuit and provided as input for a dedicated data acquisition system. Each FSR element output is routed to an analog multiplexer. An analog-to-digital converter sequentially digitizes each FSR value into an equivalent digital word to be processed by a dedicated system controller. The illustration on the right-hand side of Figure 10 shows what happens if structural damage occurs. An external force event (i.e., tool dropped on the surface) causes an impact to occur. Structural damage usually consists of multilayer delaminating or microcracking of individual composite layers. In composite structure applications, the curve for quantifying structural damage is an exponential relationship and is detected by setting a force threshold value. Exceedance of the threshold value f_x indicates that barely visible structural damage has occurred. The effects of detected damage can be read out by

maintenance personnel on a periodic basis to determine if structural repair is needed or marked as suspect and the vehicle returned to active service. A set of damage identification threshold values could be retained for each major structural component of the aircraft in a 3-D map database to perform maintenance on demand.

Conformal Antennas: A significant feature of polymer sensor array technology is the arrays' ability to operate as a low observable (LO) conformal antenna. A collocated antenna could be used to debrief sensory data to a central maintenance database in ground-support applications. The polymer sensor has been tested in laboratory conditions to detect broadband frequencies of several megahertz without any optimization of the polymer circuit pattern. The conformal antenna capability offers a significant benefit of increasing detection of "bad guy" signature threats. Tests performed by aircraft primes have indicated that conformal load-bearing antennas improve detection by a factor of 6X to 14X. In addition, the conformal polymer construction makes it suitable for phased-array antenna design for munitions and guided projectiles. Figure 11 illustrates the feasibility of using the polymer design for antenna functions.

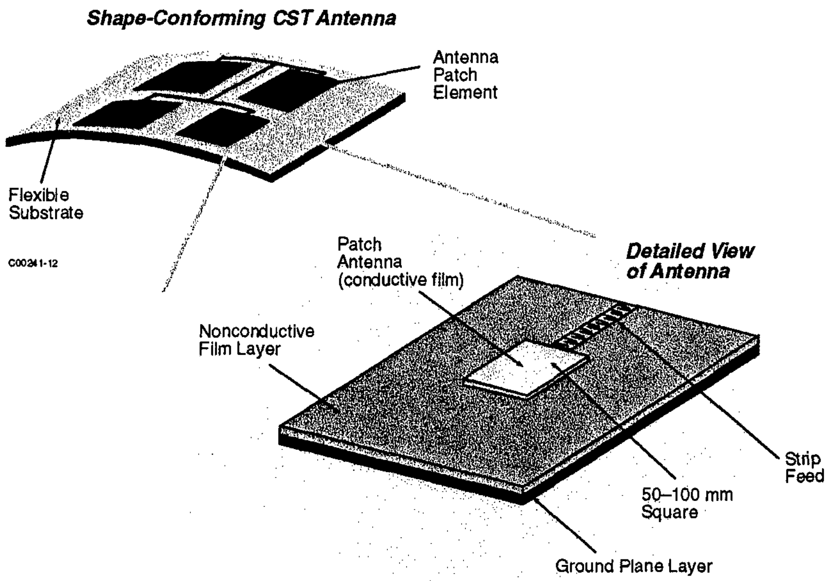

Figure 11. Example of Conformal Antenna

Figure 12 illustrates a CBM application of conductive polymer sensor arrays for machinery health monitoring. The figure highlights a PTF FSR circuit on a polymer film substrate configured as a low-cost vibration sensor. A small inertial mass is shown placed on the top of the polymer circuit which inertially loads the sensor, applying an external force related to operation of the machinery component (i.e. pump). The vibration sensor is shown mechanically bonded to pump with a pressure-sensitive adhesive tape layer. The

vibration output signal is conditioned by the co-located electronics module and transmitted via a wireless transmitter to a central maintenance database for detailed analysis and determination of pump health status. The key advantages of this type of condition monitoring are: 1) ease of placement- the conformal vibration sensor can be placed at any physical location on the pump to improve vibration pickup characteristics, and identify any structural modes of interest, 2) low cost of implementation- the polymer sensor offers significantly lower acquisition cost (x 10) than a conventional vibration sensor which presents opportunities to adding additional sensors to increase health "awareness" and improve overall system level redundancy performance.

Conclusions and Summary: The details of conductive polymer sensor arrays and their applications for structural health monitoring have been addressed. The applications of corrosion susceptibility, impact damage, and conformal antennas were presented. A conceptual view of wireless sensor web communications for field operation to support decision making and maintenance was presented.

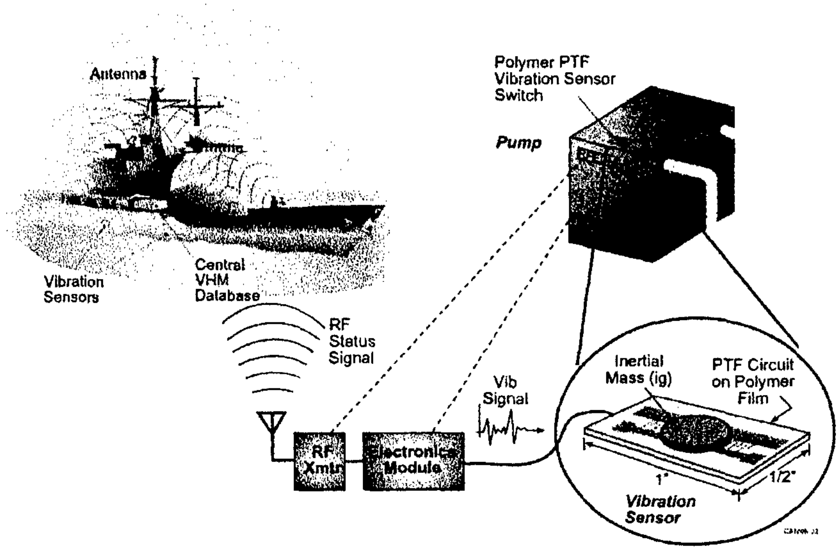

Figure 12. CBM Application of Conductive Polymer Sensor Arrays for Machinery Health Monitoring

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1. J.N. Schoess, "Aerospace Applications of Smart Materials: A Sensing Perspective Using Conductive Polymer Sensor Arrays," *Encyclopedia on Smart Materials*, (1st ed.). New York: John Wiley & Sons (2001).